Computational Needs for Muon Accelerators

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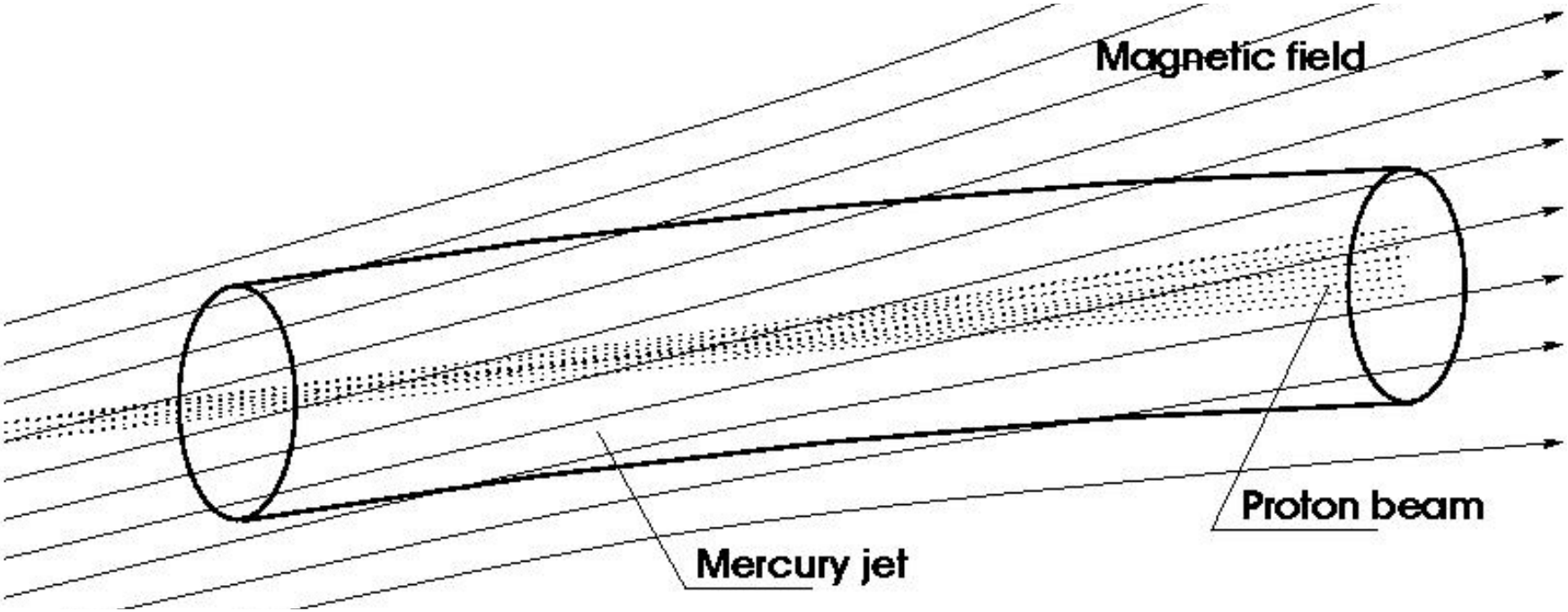
Overview

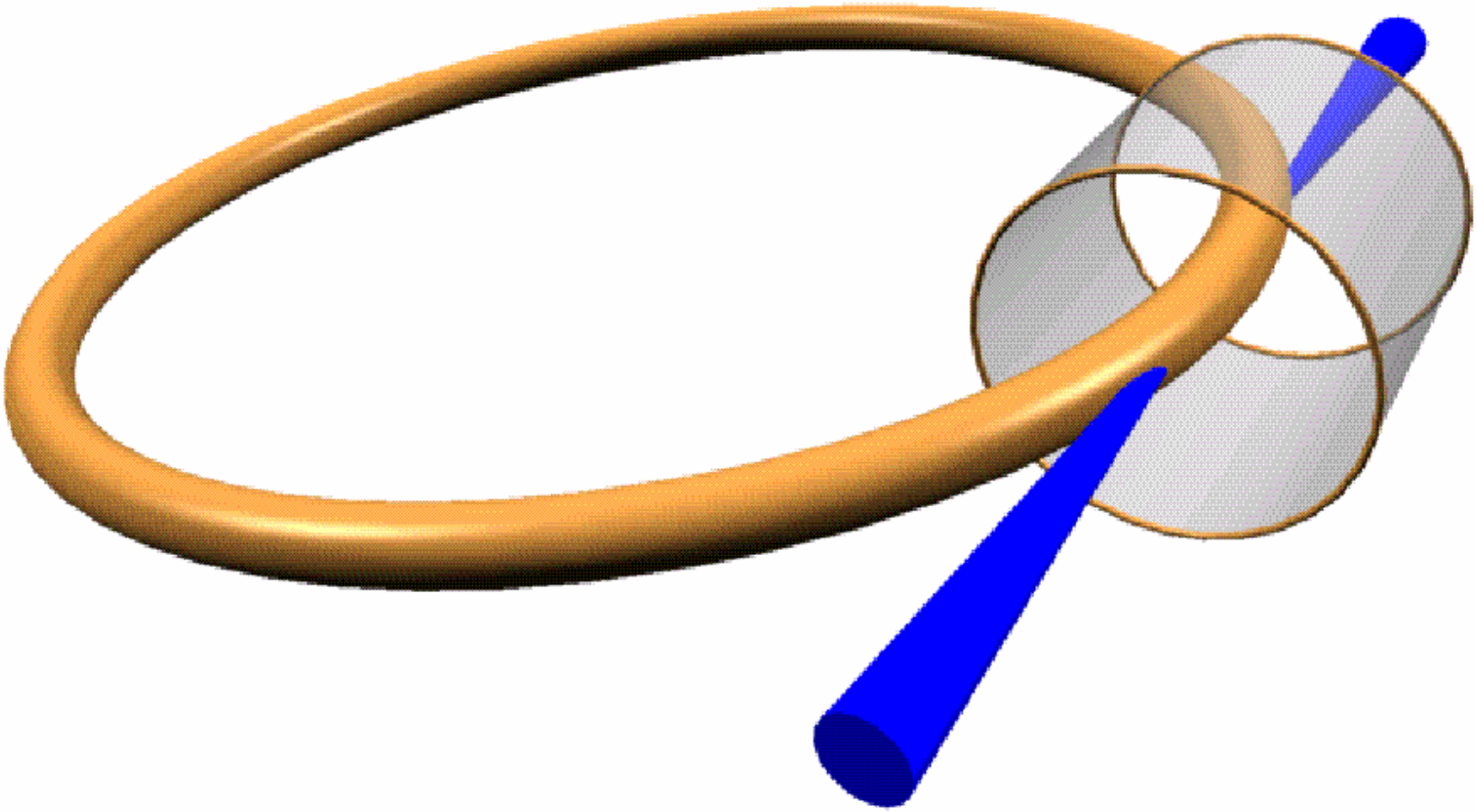
- Introduction to muon accelerators
- Beam dynamics requirements
- Target analysis

Introduction to Muon Accelerators

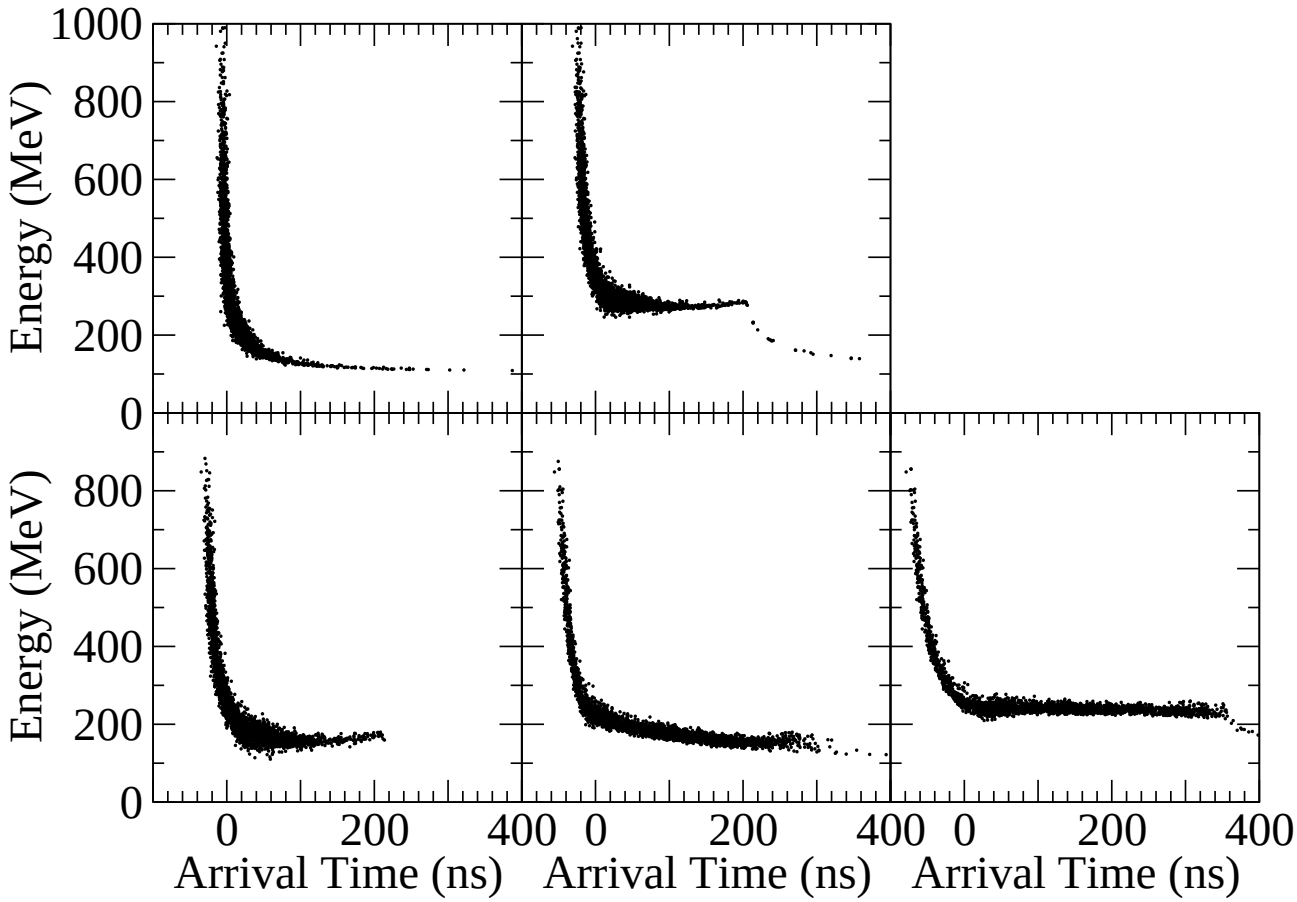
- High-power target
  - Generally at least 1 MW of protons on target, often talk of 4 MW
  - Different types of targets proposed
    - Liquid mercury (Wood's metal) jet
      - High velocity
      - In magnetic field



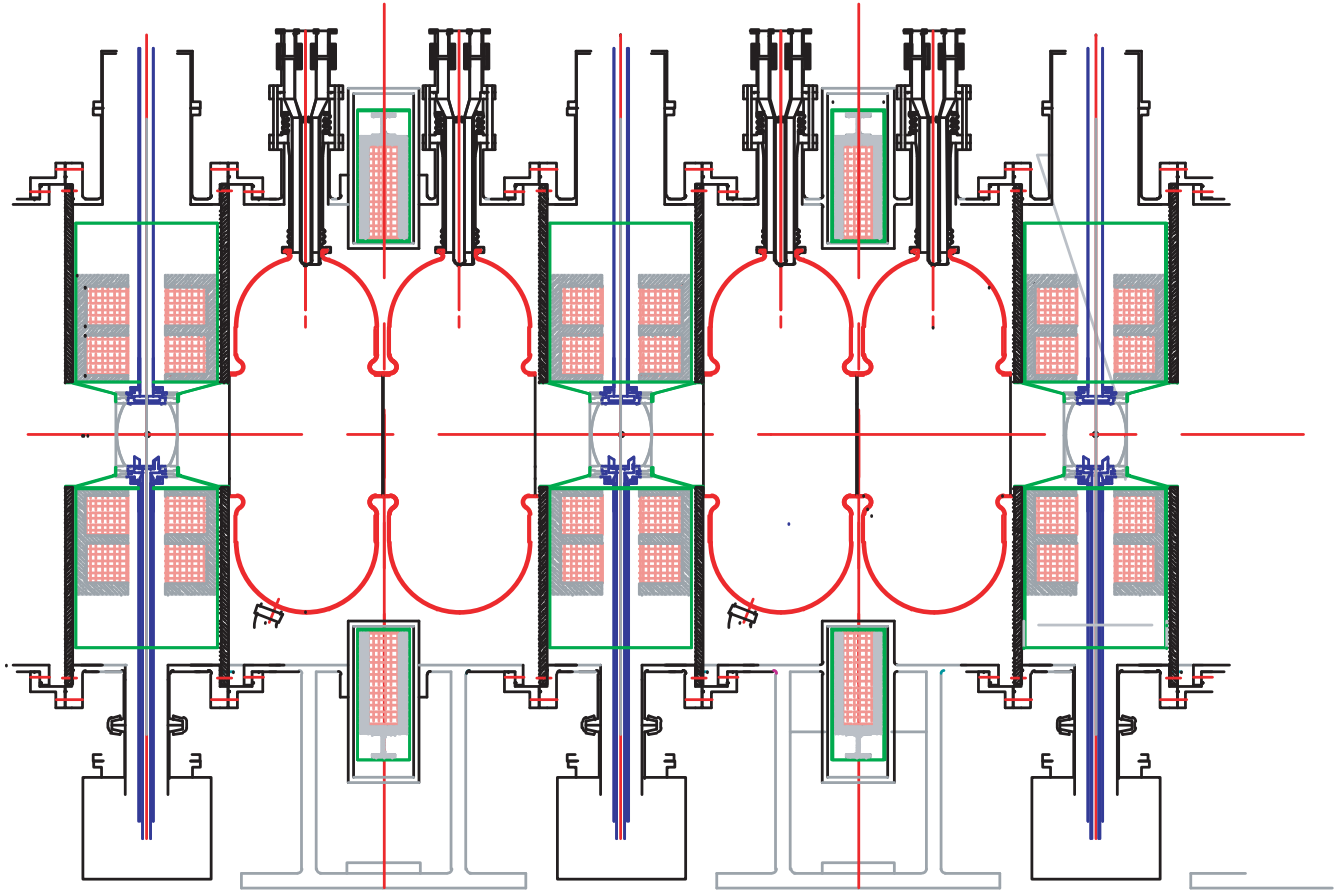
- Solid stationary targets
- Moving solid targets



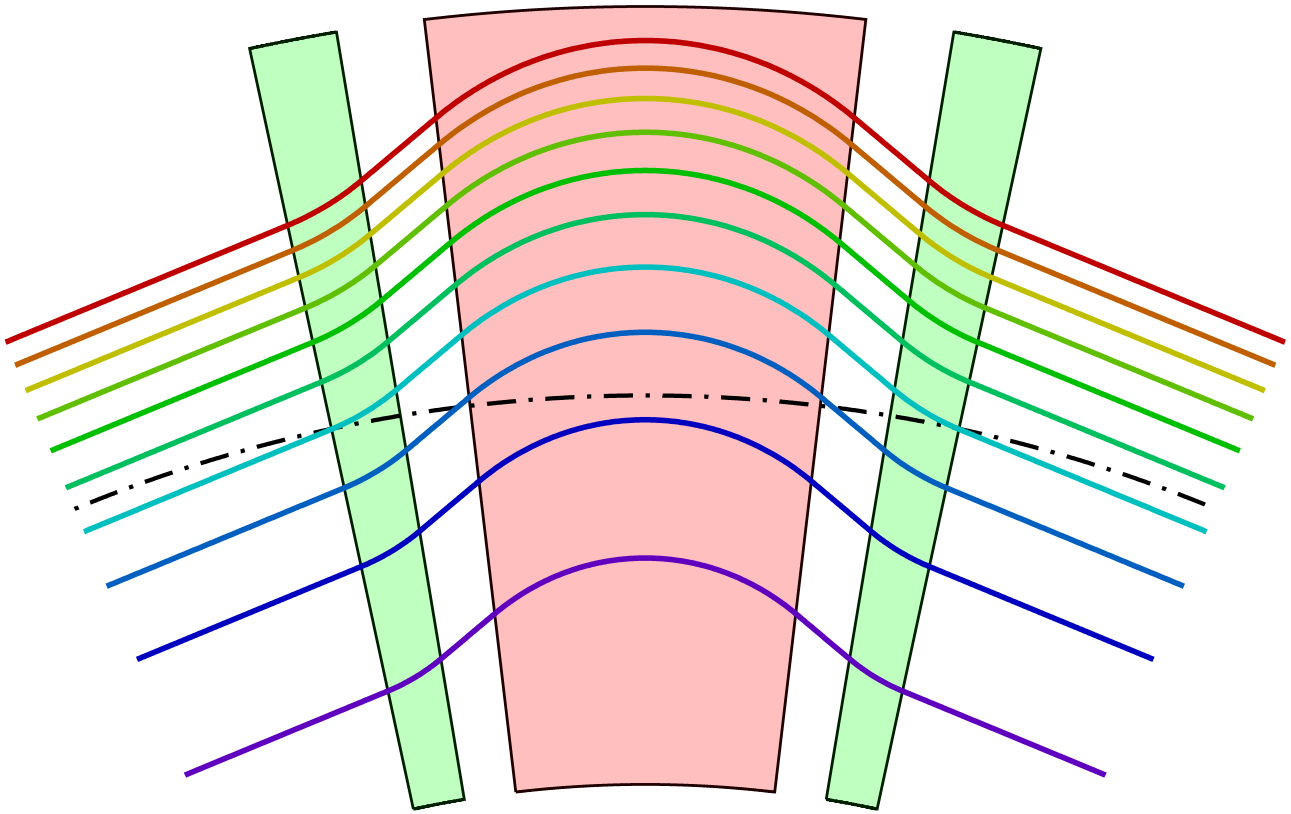
- Phase rotation
  - Large energy spread coming from target: ±50%
  - Must be reduced to about ±25% for downstream systems



- Ionization cooling
  - Reduction of transverse (and sometimes longituindal) emittance
  - Requires beam to pass through material, RF to restore lost energy



- Acceleration
  - May use Fixed Field Alternating Gradient Accelerators (FFAGs)
    - Magnets don't ramp, have factor of 2 or more in energy in same arc

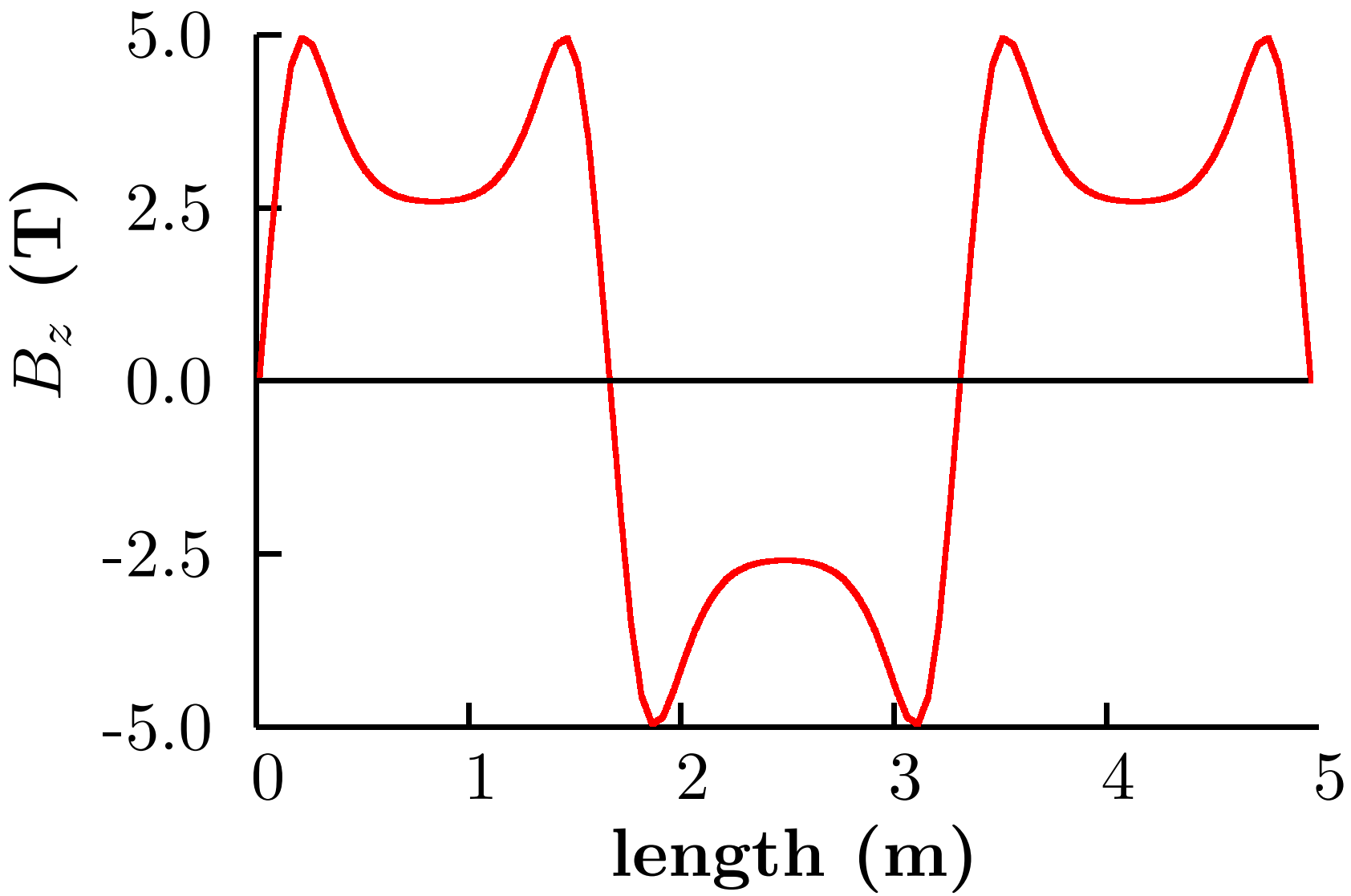


- Storage ring

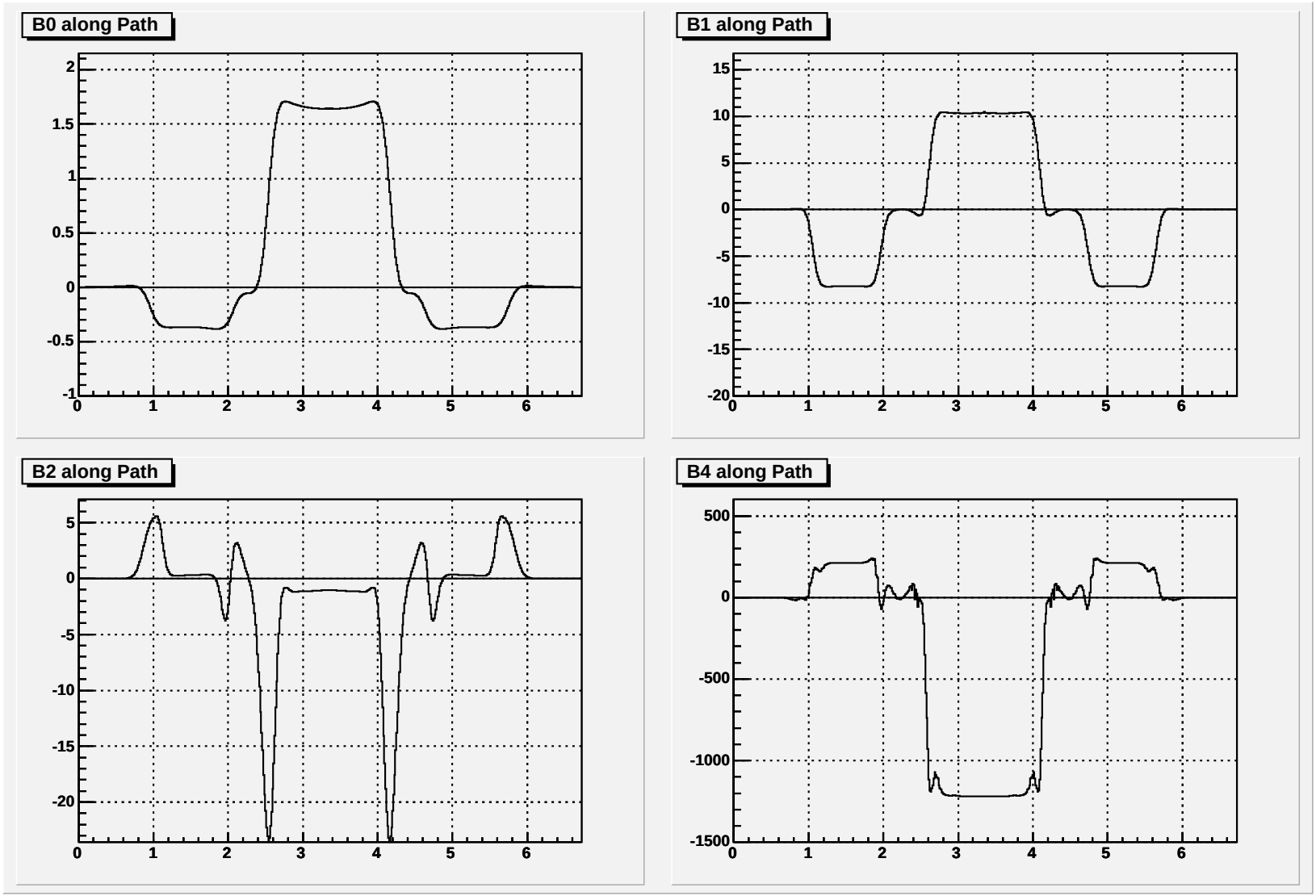
Beam Dynamics: System Characteristics

- Beamlines must accept large energy spreads
  - After target: KE from almost 0 to 300 MeV or more
  - In cooling: $\pm 25\%$
  - In acceleration: FFAGs have single beamline with a factor of 2 or more in energy
- Large transverse emittances
  - Typically the beam pipe is at 2-3σ
  - In cooling: maximum angles are around 0.1–0.2 rad
    - ⋆ Needed to keep multiple scattering under control
- Magnets are not separate, constant-field objects
  - Fields of adjacent magnets overlap
  - Fields are far from constant
  - Magnets are short compared to their apertures
    - ⋆ End fields are a significant contribution to the dynamics

Field Profile: Cooling Cell



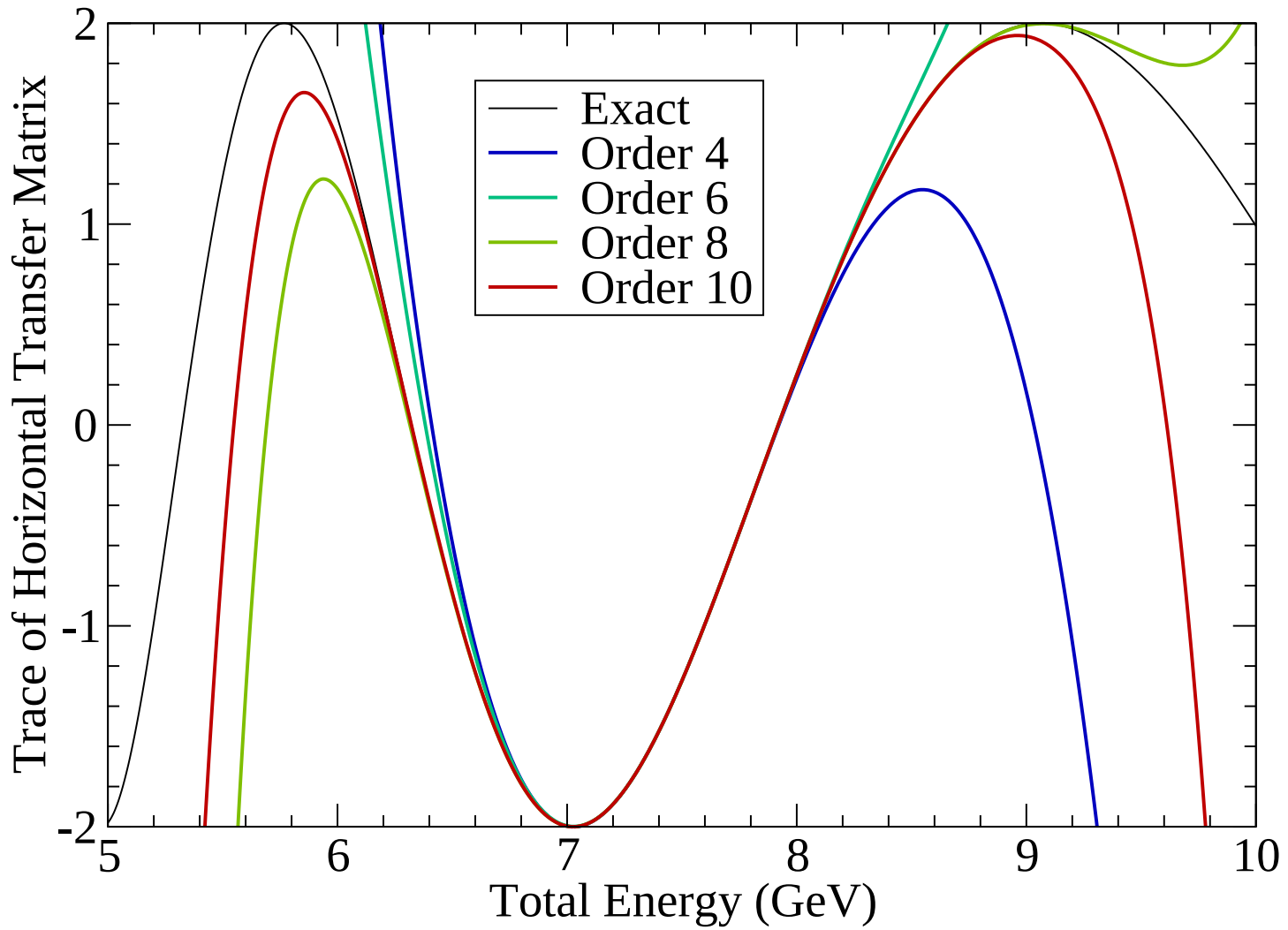
Field Profile: FFAG Cell



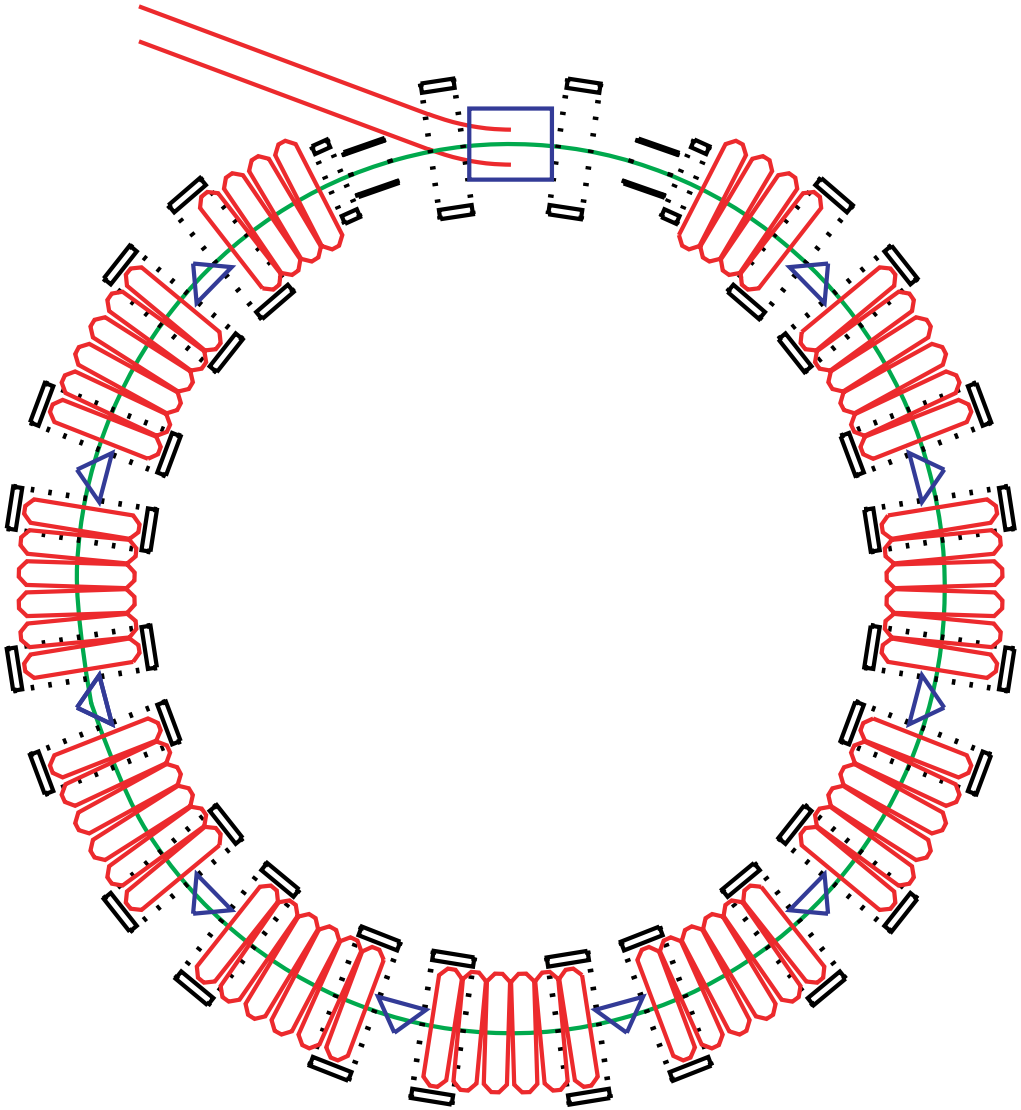
Requirements for Lattice Codes

- Correctly handle huge energy spreads, beam sizes
  - Don't approximate Hamiltonian!
  - Truncated power series present problems
    - Feed-down prevents composition of maps
    - Usually work fine for short magnets, cells
- Correctly handle non-constant fields
  - Longitudinal field variation leads to higher-order fields from Maxwell's equations
  - Model ends of magnets
- Separate coordinate system geometry from fields

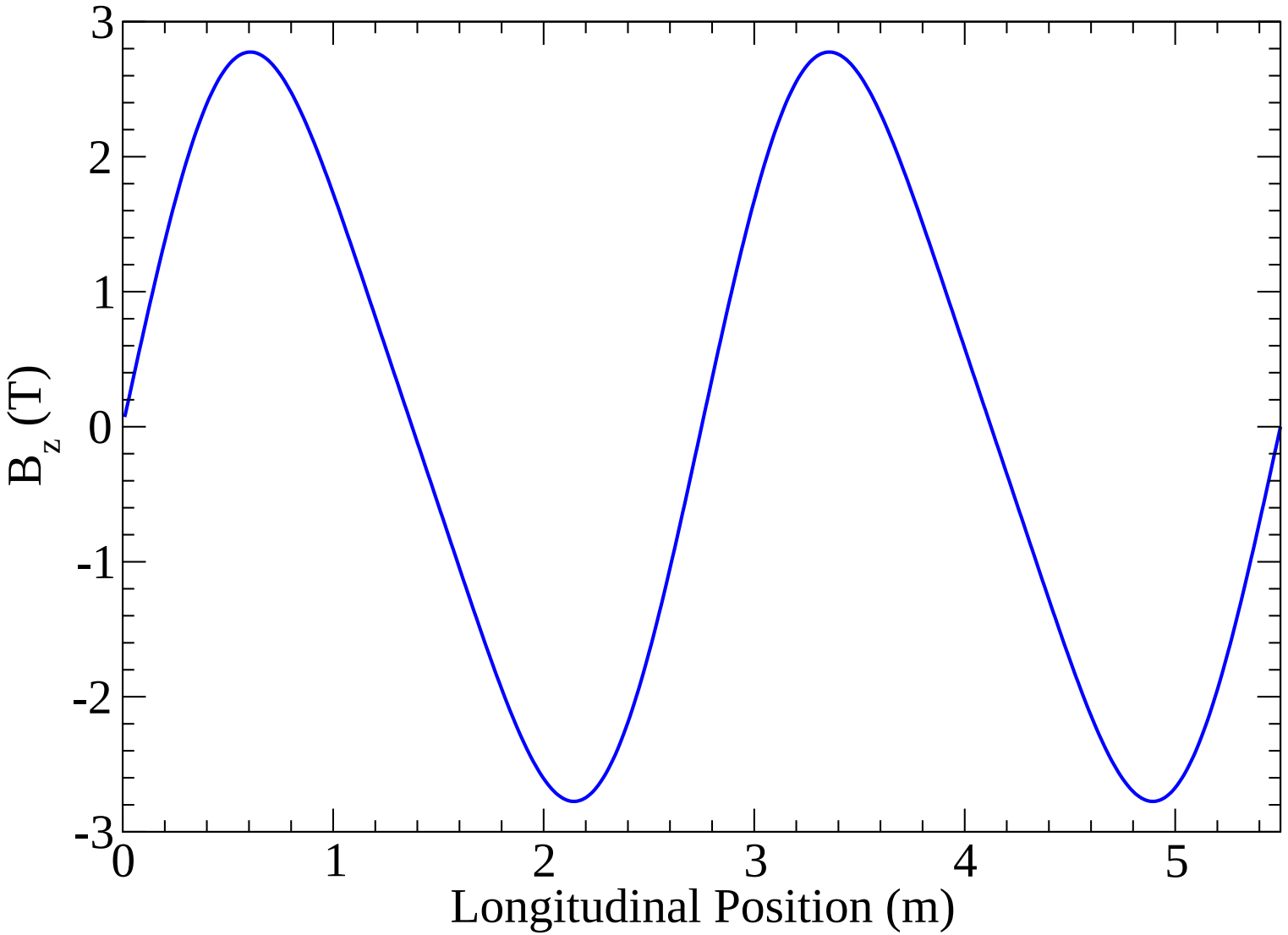
10-cell FFAG Lattice
Power Series Feed-Down



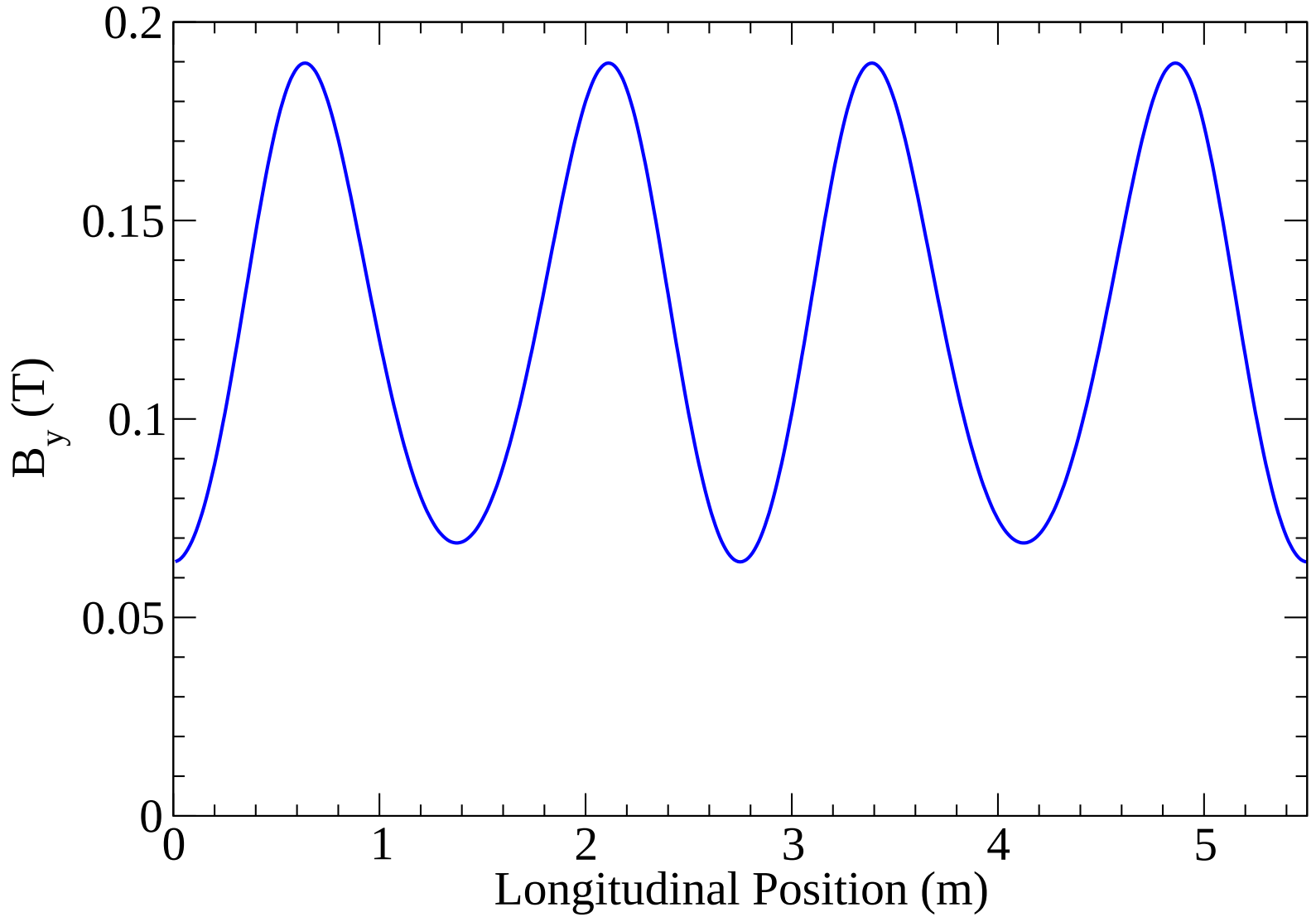
RFOFO Ring



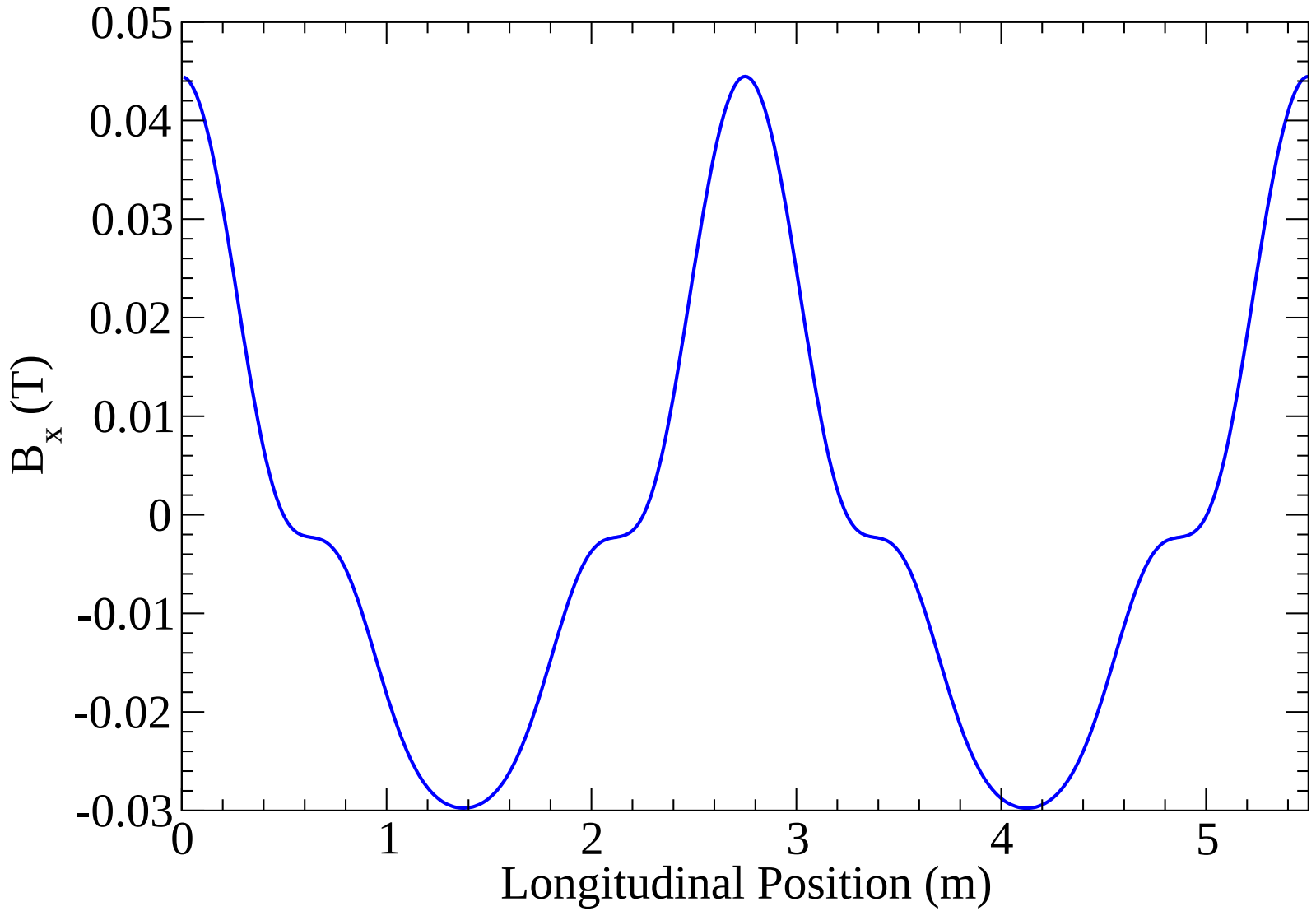
RFOFO: B_z



RFOFO: B_y



RFOFO: B_x


0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
B_x (T)
0
1
2
3
4
5
Longitudinal Position (m)

Analysis and Tracking

- Analysis codes:
  - Often have trouble with large energy ranges
  - Need to take into account cooling and multiple scattering in some averaged sense
  - Don't always match tracking (different models)
  - Need to be able to optimize rather arbitrary quantities
- Tracking codes:
  - Field computations are often slow: complex field model
  - Need many particles to compare designs accurately (poor statistics)
- Subroutine/class libraries may be more useful that monolithic tracking codes
  - We want non-standard quantities
  - Our systems often are not described in terms of standard elements

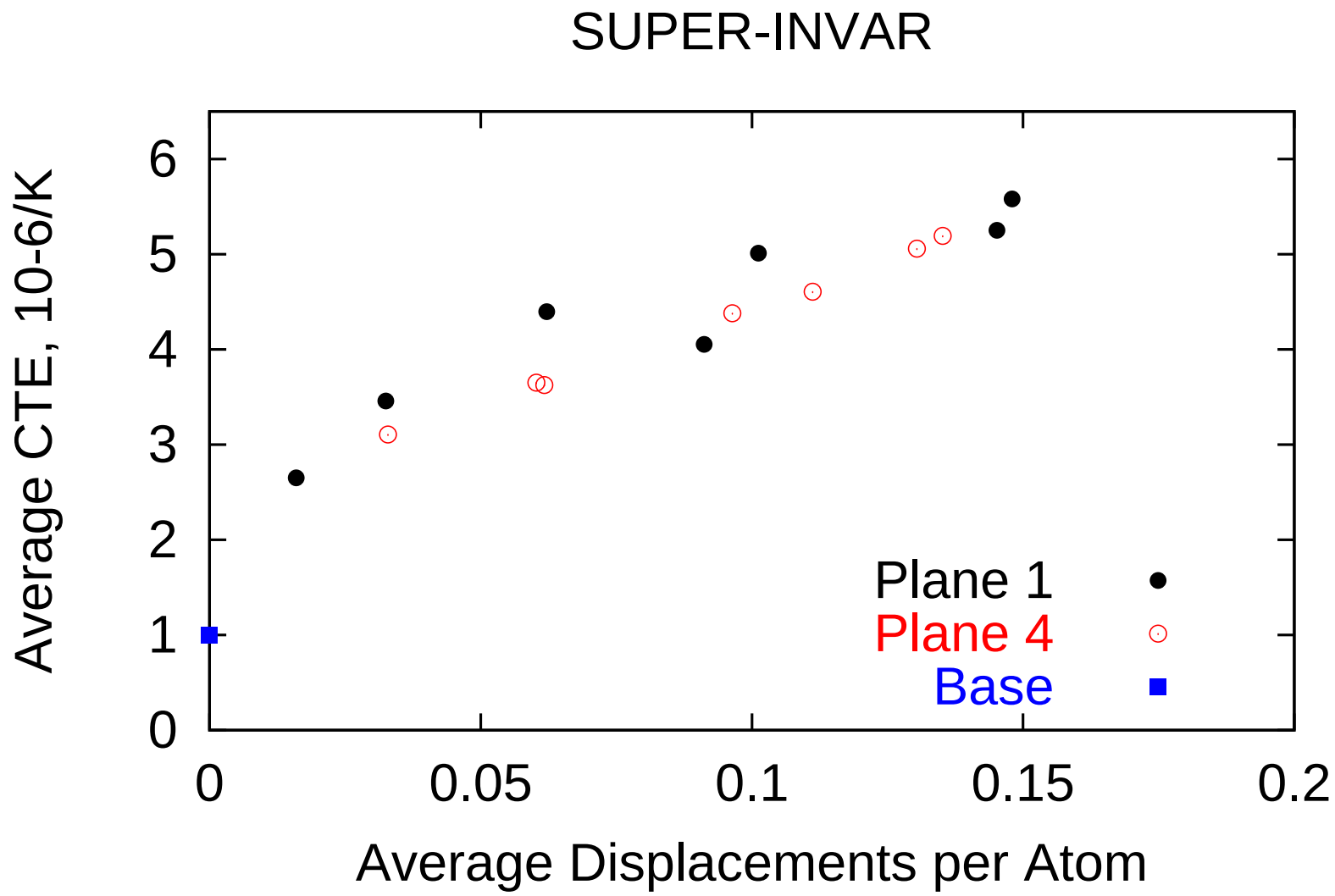
Particle Creation/Energy Deposition

- Need to be able to compute
  - Produced particle spectrum, including energy and angular spectrum
    - ⋆ Total number important for predicting performance, proton power requirements
    - ⋆ Spectrum needed for design of muon transport systems
  - Energy deposition in materials
    - ⋆ Needed for design of cooling systems
    - ⋆ Irradiation of materials: lifetime, degradation of properties, radiation protection
- Several codes which do this (MARS, FLUKA, MCNPX, . . .)
  - Significant disagreements in some cases (30%?)

Solid Targets

- Solid targets frequently break: need to predict this behavior
- Causes
  - Shock waves from beam hitting target
    - ⋆ We think we can model this fairly well
    - ⋆ Need accurate computation of energy deposition
  - Degradation of material properties under irradiation
    - ⋆ This we don’t understand well at this point

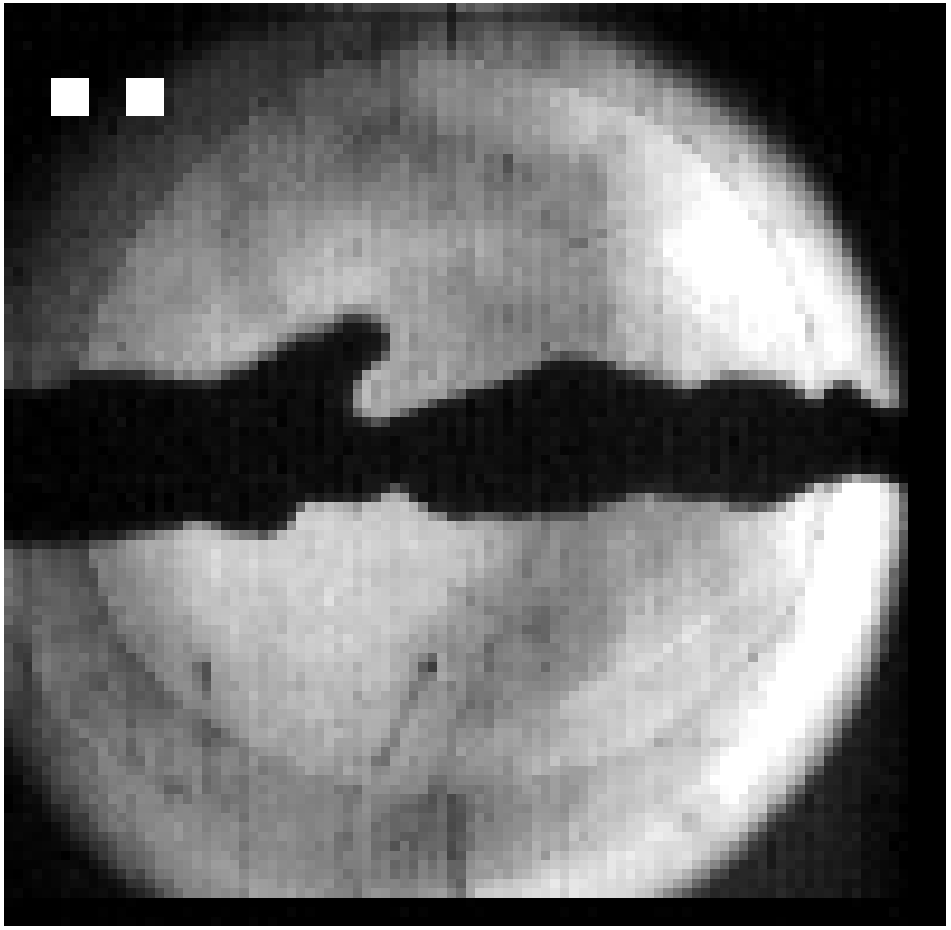
Coef. of Thermal Expansion vs. Irradiation

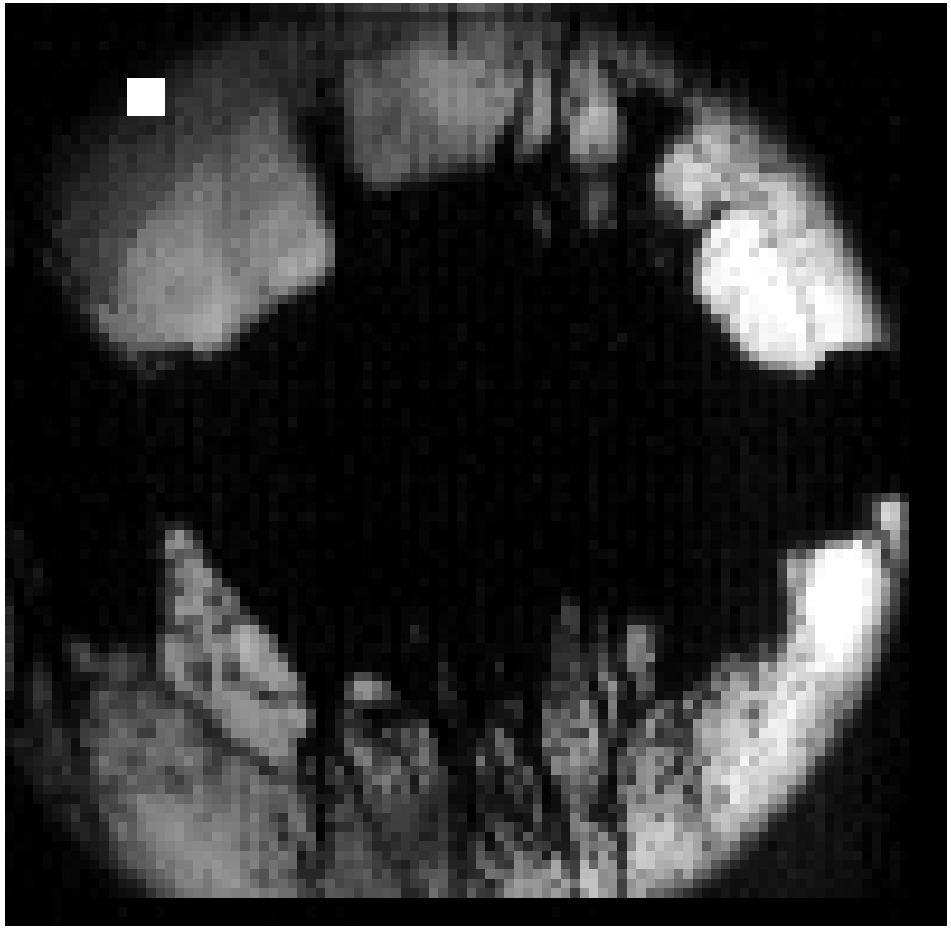


Liquid Jet Targets

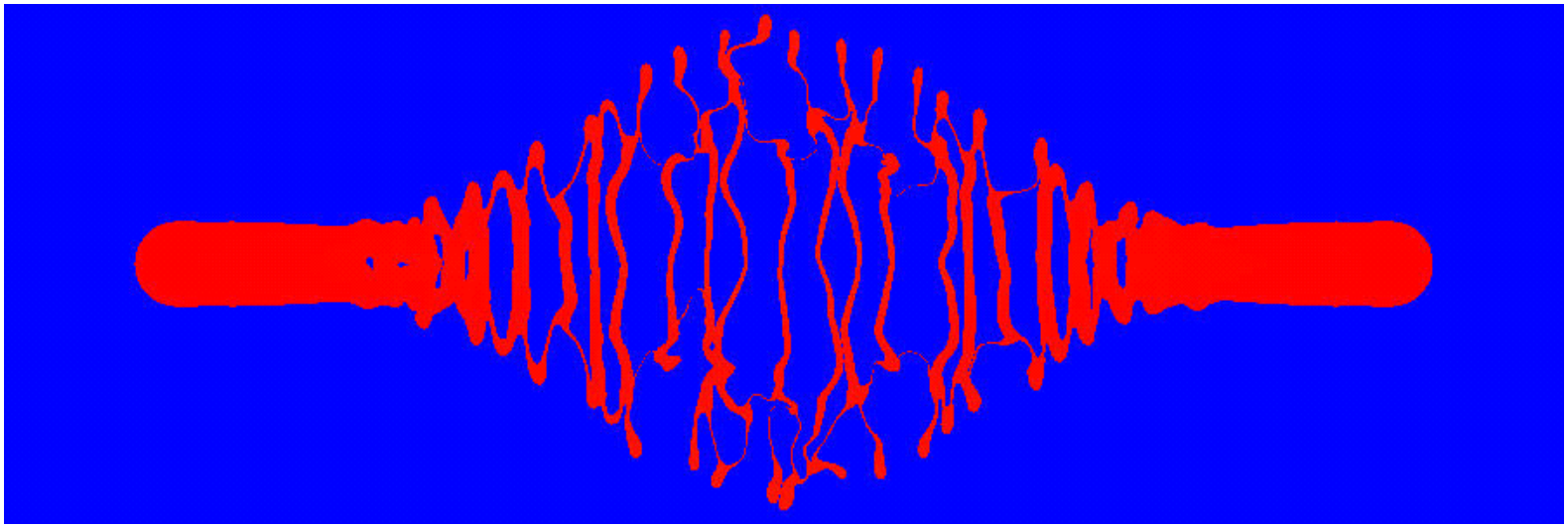
- Need to predict evolution of target
  - Will the target be stable enough to hit? Need to be able to design it!
  - Will the target be there for the next pulse?
  - Will the jet interfere with particle transport (this or next pulse)?
  - How does the jet evolve in a varying magnetic field?
- Codes exist (e.g., FRONTIER) which solve for evolution of surface
  - Cavitation caused by energy deposition and turbulence is important
  - Need model for cavitation sources!
  - Two models for cavitation in code
    - ⋆ Individual bubbles: only realistic in 2-D (3-D wouulde be nice)
    - ⋆ “Bubbly fluid” equation of state

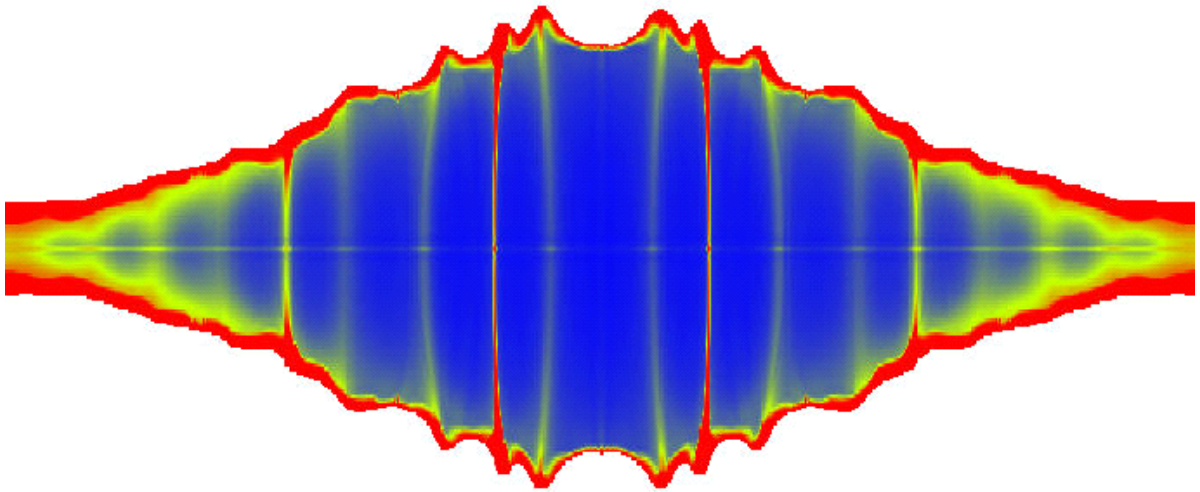
Mercury Target





Individual Bubbles and EOS Model





Cavity Breakdown

- We need to run cavities at high gradients, epecially for cooling
- Need to predict/prevent breakdown
- Good models are lacking at this point

Concluding Comments

- Large beam sizes in muon accelerators require codes that are careful to do things correctly over large ranges of phase space variables
- Target design requires a greater understanding of the physics in the targets and incorporation of that into predictive design codes